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Verification of Use of IBHVG in Screening of High-Metal Loading Igniter Materials for Optimum Ignition of JA2

by Stephen L. Howard

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14. ABSTRACT
A smorgasbord of possible reaction pairs exists for high-metals loading igniter materials. While many of these reaction pairs initially appear to perform well when looking at a simple pressure-time history, the ignition and subsequent pressurization of the candidate propellant may not fulfill the desired metrics of improvement. The interior ballistics lumped-parameter code Interior Ballistics of High-Velocity Guns (IBHVG) has been utilized to describe simple ignition in a comparative ignition fixture. The code produced pressurization curves for JA2 of a particular form factor to be used in the fixture. These pressurization curves were used as a metric standard for evaluating the "goodness" of ignition of a particular igniter. Many candidate igniters of JA2 (including standard igniters) did not exceed the metric standard and will not receive further attention for JA2, while the candidates that did exceed the performance of the metric standard will continue to be evaluated.

15. SUBJECT TERMS
IBHVG, high-metal loading, ballistic simulator, primers, MIC, thermite

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1. Introduction

Recent research has indicated that plasma ignition is a capable method to provide precision ignition, performance temperature compensation, and satisfactory ignition of high-loading density, high-energy propellants (*1–7*). However, the required electrical power supplies make this approach somewhat difficult. Recently, the advent of novel nanoenergetic materials has provided a possibility to develop "super-igniter" materials that rely upon chemical energy to mimic the following key elements of plasma performance: intense light to augment initial propellant surface area, low molecular-weight gases to penetrate complex charge geometries, and a cloud of hot metal particles to ignite multiple sites. The intense light is absorbed by the propellant most intensely at the surface exposed to the light energy, with decreasing absorbance at increased penetration depth. The propellant reacts to some extent and produces "blisters" in the bulk of the propellant where the light was absorbed. These "blisters" connect to the bulk surface, in effect creating additional surface area, and the apparent burn rate appears to be augmented (*7*). Low-molecular-weight gases on average have a higher speed than heavier gases. Therefore, the low-molecular-weight gases can travel through void spaces in the propellant bed faster than heavier gases and can spread the flame to regions of the propellant bed non-incident to the primer at a faster rate. Typical primers and igniters produce hot particles for heat transfer to the propellant so that ignition of the propellant can commence. High-metals-loading igniter materials release many of their hot particles as molten metal droplets or as metal vapor. Such hot particles can conductively transfer heat at some depth in the propellant surface. The amount of heat transferred has many factors, such as mass of droplet, velocity or degree of entrainment of droplet or vapor, and temperature of droplet. The experimental fixture and the models described in this report were designed to characterize novel igniter materials.

2. Experimental Development

Several earlier studies looked at the operating properties of the flash tube in medium-caliber ammunition (*8, 9*). The present study used a modified version of the inert simulator fixture used in these prior studies. The fixture (see figure 1) was designed to mimic the case cartridge of an LW30 30-mm round. An inert propellant bed was simulated by an air-filled region that equaled the void volume of the round had propellant been present in an actual cartridge case. A pressure tap was placed in the fixture to measure pressure in the main propellant bed region. The tap was placed on the side wall slightly above the propellant surface. The propellant sample used in each test was affixed to the end plate of the fixture so that the sample would directly receive the output from the flash tube containing the candidate igniter material used in the ignition train. Baseline measurements were made without igniter material in the flash tube. That is, the fixture was devoid of energetic material, with the exception of that contained in the M52A3B1 primer. A compositional description of the M52A3B1 primer is contained in the material safety data sheet (*10*). The primer used in the present studies was the M52A3B1 instead of the usual PA520 (the PA520 primer is used in the LW30 ammunition from which the experimental inert simulator fixture was derived).

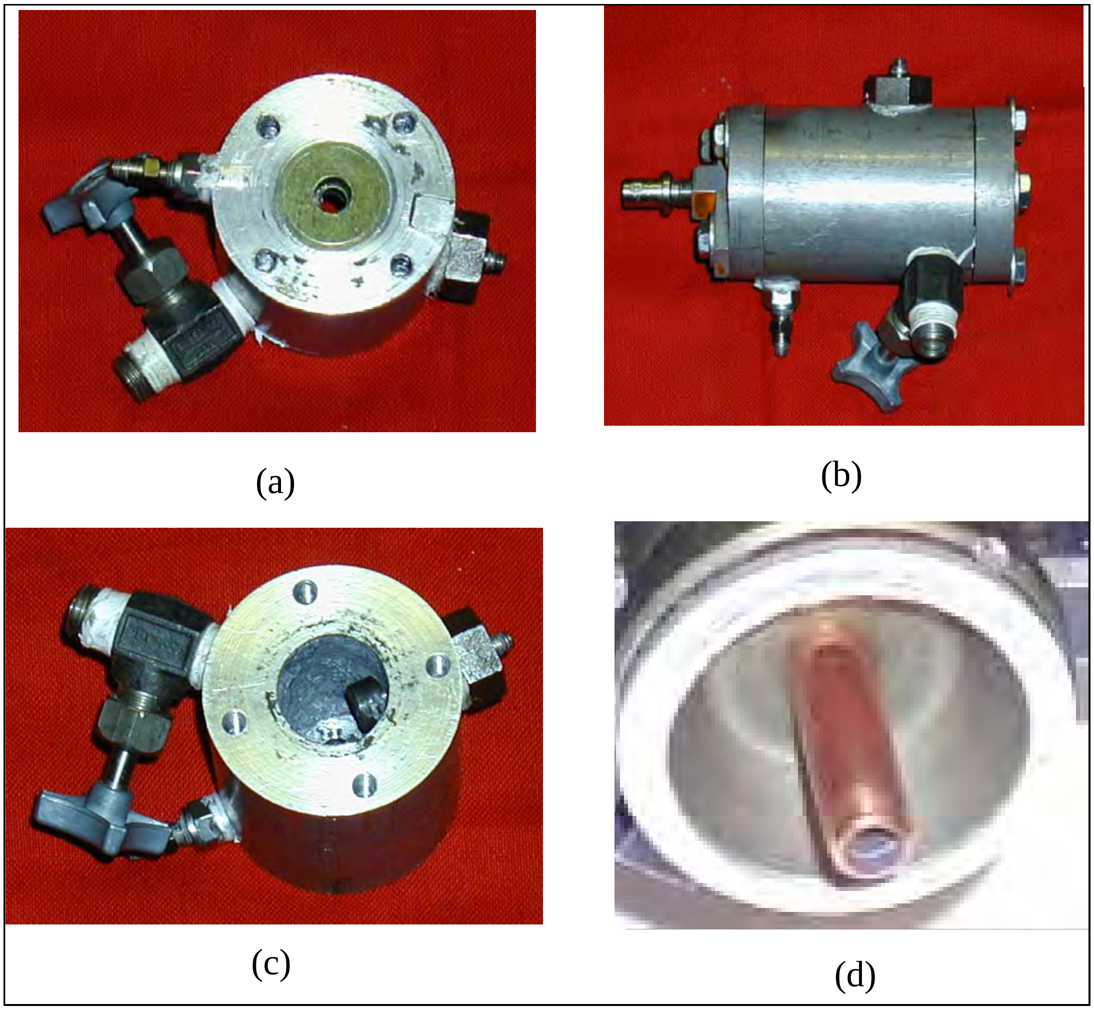


Figure 1. Simulator images showing (a) top view showing primer well, (b) side view of assembled simulator, (c) interior view of simulator from bottom, and (d) view from chamber side of installed flash tube.

In addition to the experimental baseline measurement, an experimental reference measurement was made. The reference was made relative to the LW30 standard igniter material—the IB52 pellet (*11*). The IB52 pellet is composed of BKNO3 with a gas-generating component. It was sized to fit into the flash tube used in this study. Typical LW30 usage is three pellets. For this study, only one pellet was used.

In order to form the candidate igniter material, a spherical aluminum (Al) powder with an average particle diameter of 19 nm was mixed with the appropriate oxide(s), as listed in table 1. Mixed oxides were comprised of ~50% of each oxide by weight and the required amount of Al powder adjusted on a molar basis. Ethyl alcohol solvent was added to wet the paste, and the mixture was placed in an ultrasonic bath for 30 min. The ultrasonic bath both mixed the powders on the macro scale and tended to help "pack" the oxide particles around the aluminum particles. The solvent was then removed by slow drying. The resultant powdery mixture was weighed into 0.15-g lots and pressed into pellets at ~13 MPa (see figure 2).

Table 1. Initial experimental matrix.

Test No.	Igniter Material
—	Primer baseline (M52A3B1 only)
—	IB52 reference
2	Al//CuO/Fe2O3
3	Al//Bi2O3/CuO
4	Al//Bi2O3/Fe2O3
5	Al//Bi2O3/Fe3O4
9	Al//CuO/Fe3O4
10	Al//Fe2O3
11	Al//Fe3O4
12	Al//CuO
13	Al//Bi2O3
14	Al//ZrO2
15	Al//TiO2
16	Al//Ta/CuO

Figure 2. Photograph of igniter mixture candidate 12 as both powder and pellet. Flash tube is also shown.

The propellant used for this study was JA2 in the form of a 2.5-mm-thick sheet. Adhesive aluminum foil was placed on one side of the sheet, and a 1.3-cm-diameter disk was punched from the sheet. The back side of the disk with the aluminum tape was glued to the end plate of the simulator with cyanoacrylate glue (see figure 3). The edges of the disk were not covered so that this lateral surface could participate in the initial ignition event.

Figure 3. Photograph of ignition fixture with disk propellant in place. Aluminum foil of back of propellant disk is also shown.

The M52A3B1 primer was initiated using a capacitive-resistive circuit analogous to that used in the M230 cannon, with the exception of the input power, which was full-wave-rectified 60 Hz at approximately negative 165 V (*9*). The timing of the pulse was controlled by a Special Systems sequential timer, model SSC002-010. The pulse was formed as a single-shot, square-wave pulse of variable duration, typically 0.65 ms full width. The capacitance used was 500 μF, with a limiting resistor of 100 Ω. Maximum electrical energy deposited in the primer during initiation was 0.2 J. The pressure-time histories were obtained from a Kistler 211B1 pressure gauge and recorded on a Nicolet Integra 20 digital oscilloscope prior to transfer of the data to a desktop personal computer for data analysis.

3. Results and Discussion

Many different reducing metal/metal oxide pair combinations are possible for creating high-metal loading igniter materials. Transition metal oxides are typically paired with a reactive metal, such as aluminum. The reduced transition metal then forms the metal vapor/droplet cloud that is introduced to the propellant as an ignition source. Unless gas generating materials are included in the formulation as additives or binders, the aluminum/metal oxide reactions typically do not produce much excess gas to augment the early stages of the ignition process.

While intermetallic reactions could also be considered due to energy density, they were not investigated in this study. The metal/metal oxide pairs investigated in this study are presented in table 1.

While it may not be possible to exclude all poor-performing igniter candidates based upon intelligent assumptions, choosing a good model can reduce the number of experiments in obtaining a good candidate. The first model attempted was based upon the high adiabatic temperature possible with the reactive metal/metal oxide reaction, and the second model attempted was based upon the high specific energy of the reaction. The theoretical adiabatic temperature and the specific heat of reaction were obtained from a published reference (*12*). These values established the x-ordinate values for the two proposed thermochemical models. The y-ordinate was proposed to be the time to maximum pressure of the JA2 combustion in the simulator fixture.

Since a theoretical model was not available to estimate the time to maximum pressure in the simulator fixture with an igniter material in the flash tube and a JA2 propellant disk as energetic material, several experiments were made with different reaction pairs igniting a JA2 disk. It was found that if the time to maximum pressure in the fixture was plotted against the reciprocal of the theoretical adiabatic temperature (values of theoretical adiabatic temperature were obtained from published values [*12*]) of the reaction, a straight-line plot could be obtained with good confidence (see figure 4). This plot is reminiscent of Arrhenius activation energy plots, so it could be relevant. Figure 4 also shows predictions of several high-temperature reactions that have not been experimentally attempted. In this model, the predictions lie close to the plotted straight line. The error bars shown for these predictions are those showing the time to maximum pressure predicted from the second model (see figure 5).

The second model (figure 5) was based upon a straight-line plot of experimental time to maximum pressures plotted against the specific energy theoretically available from a particular reactive metal/metal oxide reaction (values of theoretical specific energy were obtained from published values [*12*]). While the correlation is not as good as for the first model, the four predicted reactions were added to the plot. As shown in figure 5, the predicted values of this model that would be located on the line have appreciable error when compared to the time to maximum pressures predicted by the first model (error bars similar to those in figure 4). It was decided that although each model by itself seemed to be founded upon good principles, neither one was sufficient for the perceived needs.

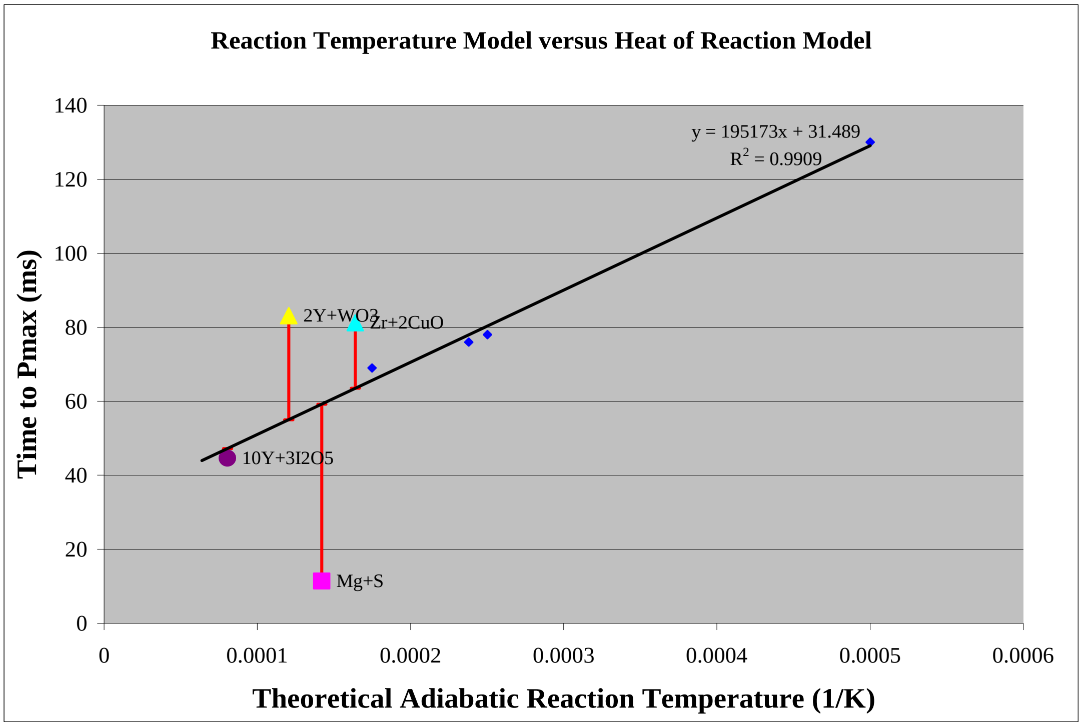


Figure 4. Arrhenius-type plot of metal/metal oxide reactions with experimental values in blue and four predicted reactions. Off-line points indicate values of the four predicted reactions using the specific-energy model.

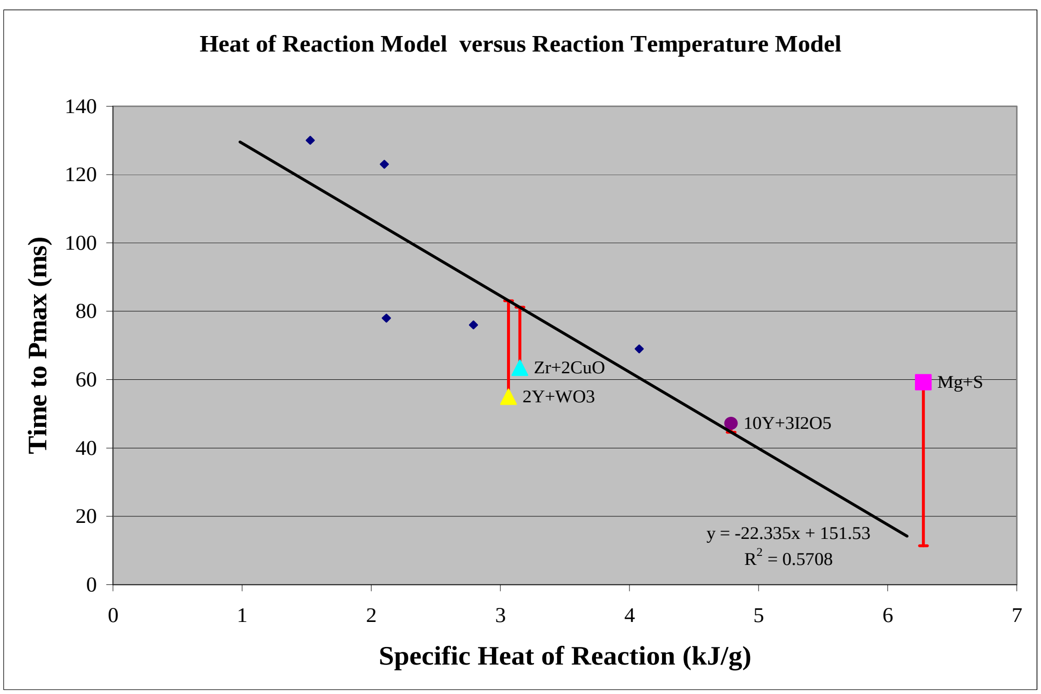


Figure 5. Heat of reaction model with experimental values in blue and four predicted reactions. Off-line points indicate values of the four predicted reactions using the reaction temperature model.

These two thermodynamic models were focused on the igniter materials. Therefore, the next model to investigate was designed to focus on the propellant and ignore the igniter material. For this purpose, one of the interior ballistics codes available at the U.S. Army Research Laboratory (ARL) was selected. Interior Ballistics of High-Velocity Guns (IBHVG) is a simple, lumped-parameter code that does not use igniter-specific details for our case (other than initial pressure) but does require propellant-specific information, such as composition and available surface area. The code also required the chamber volume and the chamber material (aluminum) for heat loss. Since the chamber volume of the simulator fixture is fixed, the gun bore resistance for IBHVG was much larger than the available pressure, so the projectile would not move to any extent so that condition of constant volume was maintained.

The igniter for the model was the ideal igniter with the outer layer of all available surface area of the propellant ignited equally in time and intensity. The initial pressure of the chamber for the model was the maximum pressure measured experimentally when only the primer was ignited in the chamber, in other words, the maximum chamber pressure measured when no energetic materials other than that in the M52A3B1 were in the chamber. Hot particles from the M52A3B1 were ignored for initial conditions in the model. Therefore, the "ideal igniter" was modeled as equally igniting all available JA2 surfaces equally at the initial pressure equal to the maximum pressure produced by the experimental primer. If an experimental igniter could equal or exceed the ideal igniter, then it would merit further investigation; if the experimental igniter could not equal the performance of the ideal igniter, then that candidate could be removed from the experimental matrix, thereby reducing additional experiments.

The model was constructed (see pictorial view in figure 6) and the test conditions evaluated. The ignition stimulus was only desired on the top and lateral surfaces of the propellant disk. Therefore, aluminum foil backing was added to the propellant disk to prevent ignition on the back surface. The initial pressure in the fixture chamber was determined from the experimental value of the primer-only ignition into the empty chamber of the fixture in figure 1 (no propellant or candidate igniter material present for this test, maximum pressure attained was considered to be the pressure available from the primer). The propellant disk was right-cylindrical in form and punched from JA2 sheet stock 2.54 mm thick, with a diameter of 13.0 mm. The total ignition surface area was 235 mm^2.

Typical thermochemical values of JA2 were used to compute the burn rate and combustion of the propellant (see appendix for input deck information and JA2 thermodynamic values used). The values of interest computed from the model (figure 7) were the chamber pressure as a function of time until burn out and the pressurization rate as a function of time. If a different propellant, different shape of propellant grain, or different experimental fixture were to be used, the model would need to be modified for these considerations.

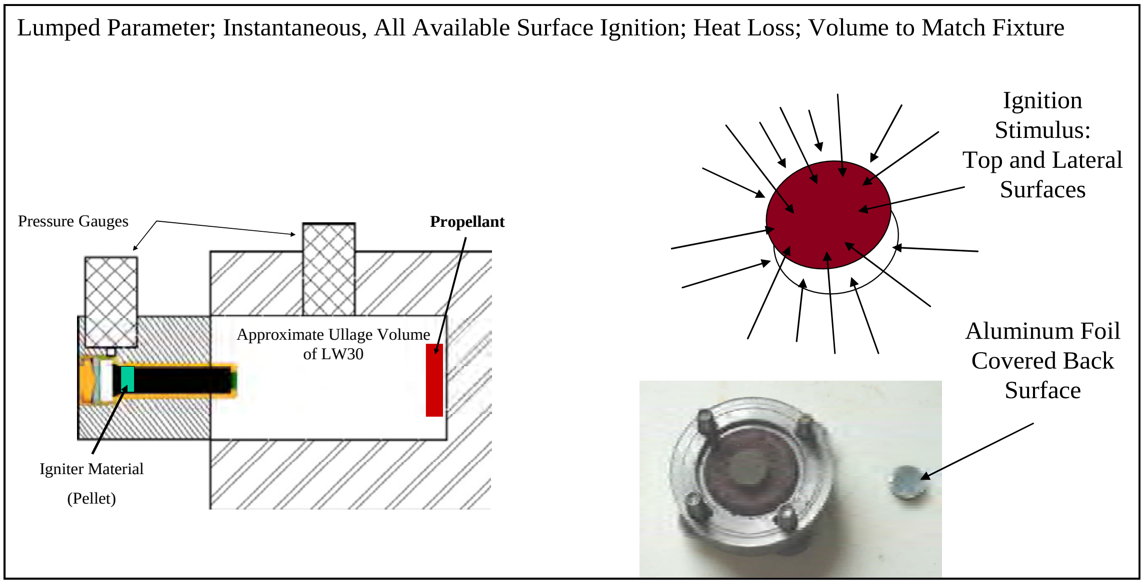


Figure 6. Pictorial of elements used to construct the IBHVG model for JA2 in the fixture in figure 1.

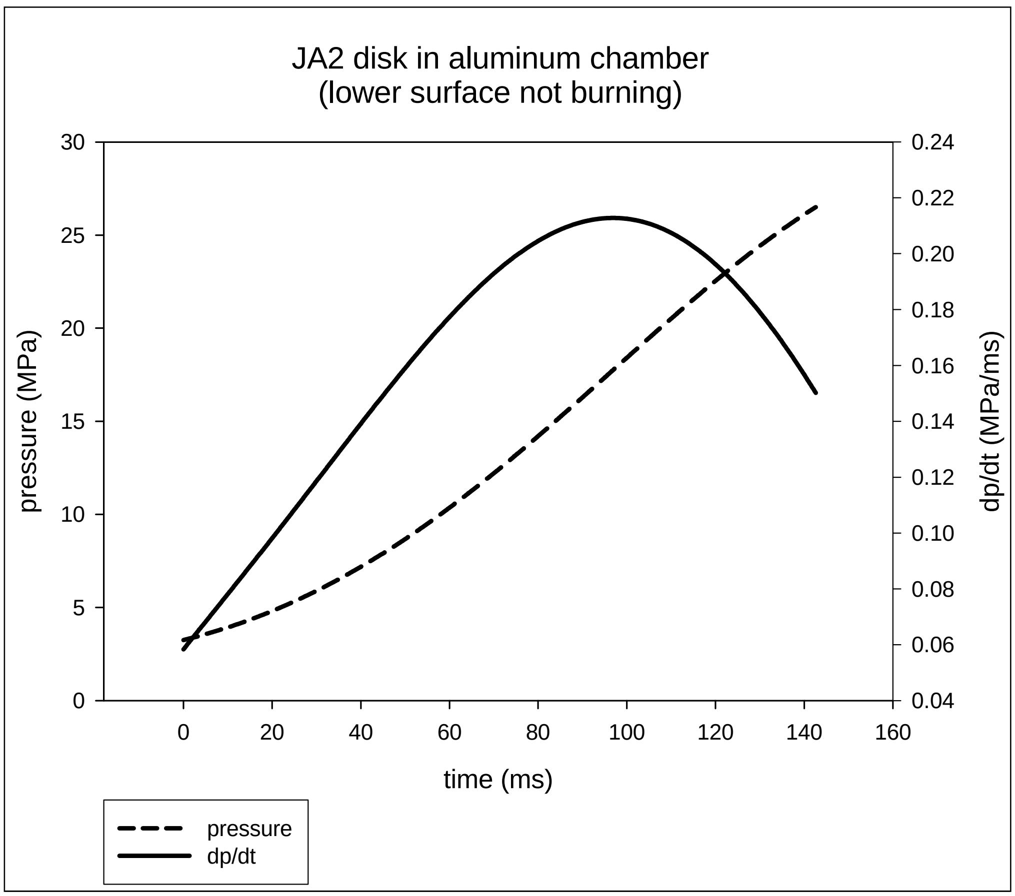
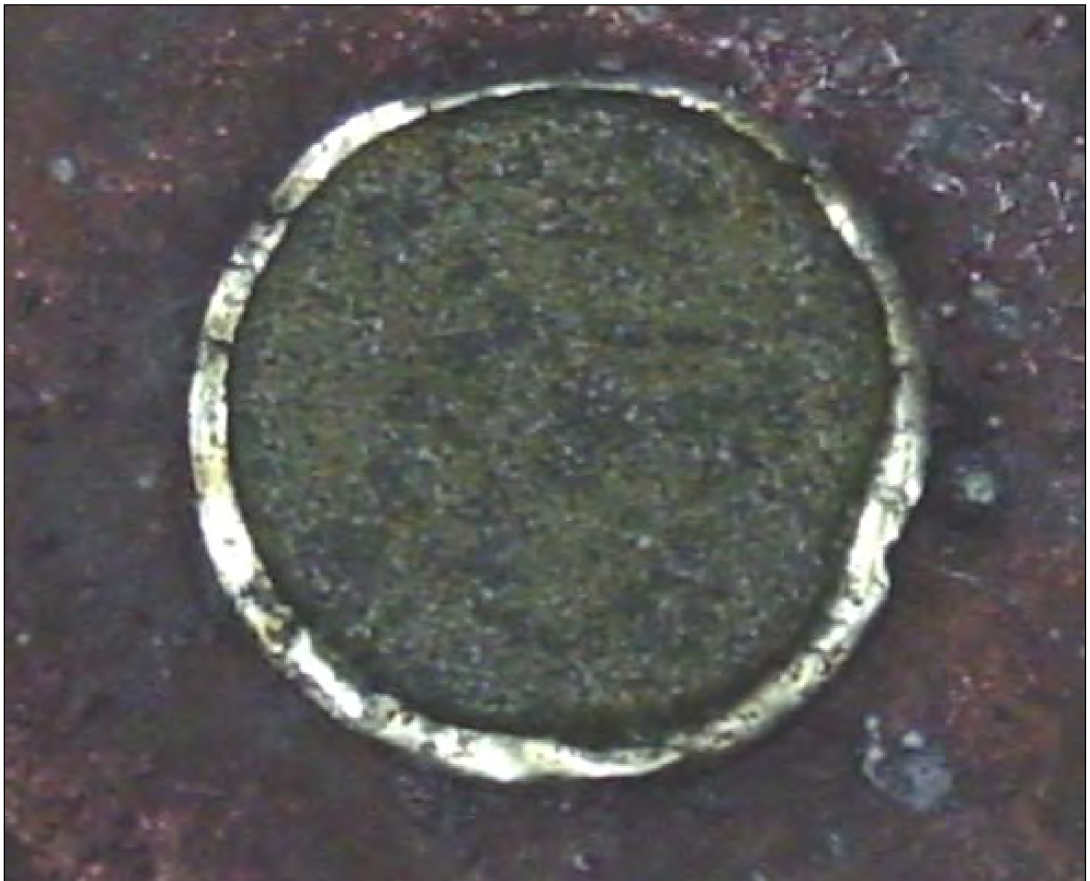


Figure 7. Plots of pressure-time history and pressurization rate for ideal ignition of JA2 in fixture, as calculated by IBHVG.

A measure of the uniformity of ignition and regression required by the model was experimentally verified by interrupting the burn of a particular experiment using igniter material number 12 (see table 1). After the burning of the JA2 was quenched, the regression of the top and lateral surfaces was measured (see figure 8). As is easily noted, the amount of aluminum backing foil that was uncovered by the combustion process was fairly uniform along the outer diameter of the disk. Within measurement error, the regression of the lateral and top surfaces matched that expected for proper model operation (essentially equal regression on both surfaces).



Surface Regression:	0.6 mm	lateral
	0.5 mm	top surface

Figure 8. Photograph of JA2 disk after interrupted burn showing regression of surfaces (aluminum backing foil showing around edges).

A number of experiments were then performed using igniter materials from table 1. The pressure-time histories produced were compared with the model pressure-time history in figure 7. According to the screening rule setup earlier (i.e., ignition must equal or exceed that of the ideal igniter), the experiments whose pressure-time histories lie entirely on the right-hand side of the model values in figure 9 will not receive further consideration. The experiments whose pressure-time histories lie to the left of the model values remain for further evaluation. It should also be noted that some of the pressure-time histories lie on both sides of the model. With comparison using pressure-time histories alone, it was difficult to determine the magnitude of agreement with the screening rule.

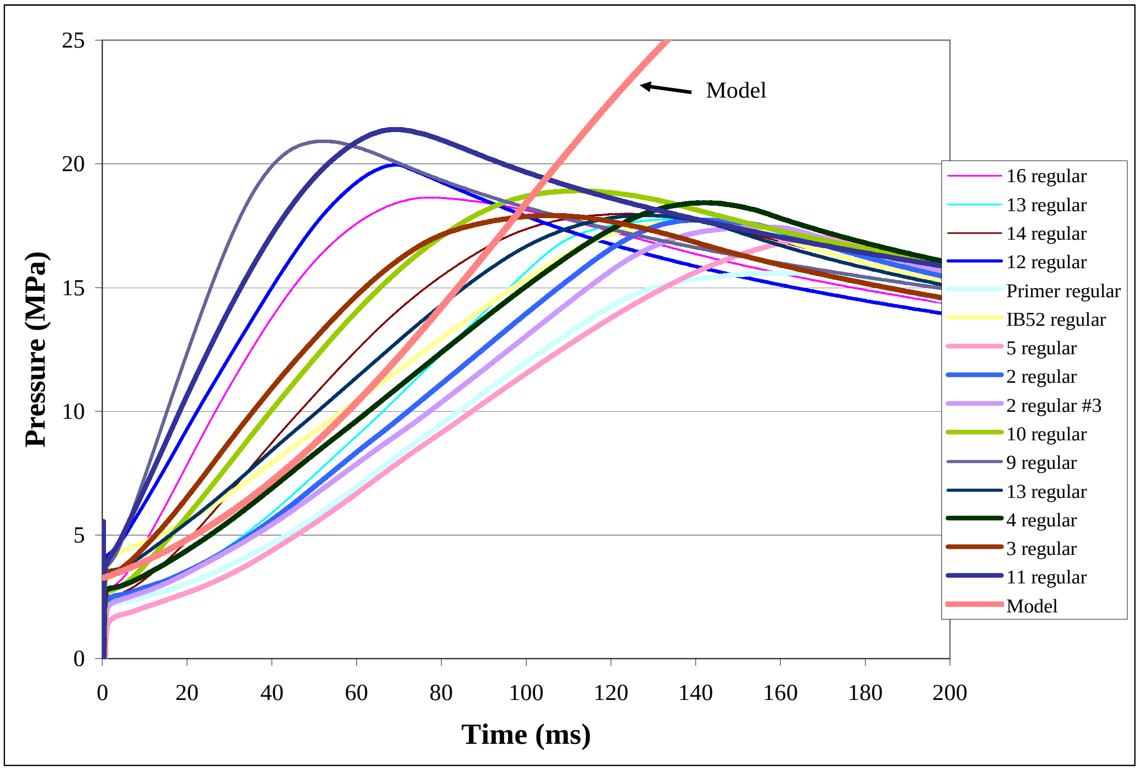


Figure 9. Pressure-time histories of selected experiments using igniter materials from table 1. Comparison with model values shown.

It can be noted in figure 9 that ignition in the case of primer-only stimulus (experimental baseline case) was always less than that of the model. The reference igniter material utilizing the IB52 pellet (standard igniter material) met or exceeded the model pressure values at various portions of the history. However, upon examination of the pressurization rates in figure 10, it was obvious that the standard reference ignition equaled the model values only from 21–35 ms. At no time did it exceed the model values. Therefore, both the baseline and reference igniters were removed from the continuation experimental matrix.

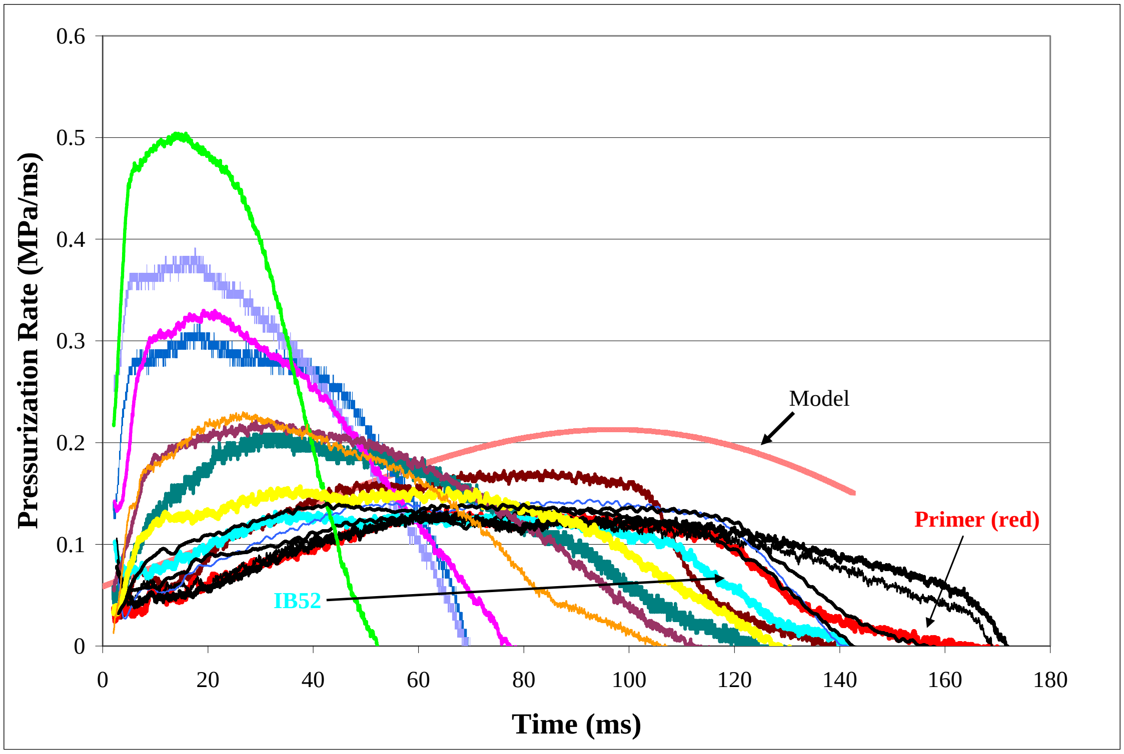


Figure 10. Plots of pressurization rates from experiments shown in figure 9. Comparison with model values shown.

Of the remaining igniters that passed the model expectations in figure 9, a quick look at figure 10 shows that these igniters also exceed the model expectations in terms of pressurization rate and do so more clearly. These candidates seem to fall into roughly three groups, with some outperforming the others. While these trends were not easily evident using the pressure-time histories in figure 9, the use of pressurization rates in figure 10 simplifies the elimination of candidates by graphical means. Using figures 9 and 10 to screen the experimental igniters to date has reduced the candidates meriting further examination in this study from 14 to a maximum of 4 (see table 2).

Table 2. Reduced experimental matrix.

Test No.	Igniter Material
9	Al//CuO/Fe3O4
11	Al//Fe3O4
12	Al//CuO
16	Al//Ta/CuO

4. Summary

Two thermochemical models for evaluation of the viability of metal/metal oxide igniters were developed. These models were invariant with respect to the propellant to be ignited and only regarded the candidate reactive metal and metal oxide thermochemical properties. When the two models were used for prediction of igniter behavior, the cohesiveness of the models showed that they were inadequate.

A third model was then attempted. This model was invariant with regard to the reactive metal and metal oxide properties. Instead, it focused on the propellant and experimental fixture properties. This model was developed using an interior ballistics code at ARL, IBHVG.

This model determined the pressure-time histories and pressurization rates for a JA2 propellant sample of a particular size and shape to be ignited in a particular igniter fixture. Using JA2 for the propellant and the LW30 inert simulator at ARL, the pressure-time histories and pressurization rates were used to screen an experimental matrix of 14 candidates. This screening reduced the matrix to a maximum of four candidates for further study.

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Appendix. IBHVG Input Deck Used in JA2 Model

This appendix appears in its original form, without editorial change.

```
$COMM
   100mm progressivity sphere
$HEAT
   TSHL = 0.0001143     CSHL = 900.      RSHL = 2700.
   TWAL = 293           H0   = 250.    HL   = 1
$GUN
   NAME = '100mm special'    CHAM = 0.0000225   GRVE = 0.1
   LAND = 0.1         G/L  = 1.      TRAV = 0.001
   TWST = 99
$PROJ
   NAME = '100mm special'   PRWT = 1.
$RESI
   NPTS = 2             AIR  = 0
   TRAV = 0,.01
   PRES = 100., 0.
$INFO
   RUN  = 'lower surface not burning'   DELT = 5E-5  DELP = 1E-4
   GRAD = 1             POPT = 1,2,1,0,2    SOPT = 0
   EPS  = 0.05
$TDIS
    SHOW='TIME'
$TDIS
    SHOW='TRAV'
$TDIS
    SHOW='VEL'
$TDIS
    SHOW='ACCL'
```

```
$TDIS
     SHOW='BRCH'
$TDIS
     SHOW='MEAN'
$TDIS
     SHOW='BASE'
$TDIS
     SHOW='TBAR'
$TDIS
     SHOW='Z(1)'
$TDIS
     SHOW='PDOT'
$RECO
    NAME = 'NONE'      RECO = 0        RCWT = 0
$PRIM
    NAME = 'BP'        CHWT = 0.00013
    GAMA = 1.221        FORC = 548700.
    COV  = 0.0009747145  TEMP = 2041
$PROP
    NAME = 'JA2 7P GRAN'    CHWT = .000642    GRAN = 'CORD'
    RHO  = 1595.2      GAMA = 1.2268     FORC = 1150907.
    COV  = 0.0009747145  TEMP = 3436      EROS = 0.0000000
    NTBL = -2 PR4L=68.96,700.  CF4L=.0017945,.00091665 EX4L=.7162,.8796
    LEN  = 0.003175     DIAM = 0.0127
    WEB=.003175
$END.
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J COLBURN
P CONROY
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